Arizona I-19 WiFi Corridor: Concept Demonstration of Probe Vehicle Tracking

Report TRQS-03

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Executive Summary

The Vehicle Infrastructure Integration (VII) initiative of the U.S. Department of Transportation plans to enhance roadway safety and traffic management with an advanced wireless data communication infrastructure. The system as envisioned will include a network of roadside units communicating with vehicles using Dedicated Short Range Communications (DSRC). Vehicles equipped to send data to a central location in this way are called probe vehicles. It will be many years before the costly network of DSRC roadside units is constructed. In the meantime, many cities and other public and private entities are installing WiFi networks along roadways, which may provide the same capabilities as the DSRC. WiFi has never been used to support a probe vehicle system. The purpose of this project is to demonstrate the feasibility of WiFi by equipping a passenger car as a probe vehicle, and testing it along the I-19 WiFi Corridor.

Numerous experimental and commercial probe vehicle systems have been developed in the U.S., Europe, and Japan. They have used a variety of communication technologies, including DSRC, cellular, satellite, and radio. The most successful systems use taxis as the probe vehicles, since the communication mechanism is already in place. WiFi offers the same benefit because it provides other services for a large user base. The I-19 WiFi Corridor from Rio Rico to Green Valley provides an ideal test bed for this project because it was designed for mobile applications. The architecture supports complete coverage of the freeway and rapid handoff between nodes.

Qameleon Technology builds instruments, based on a common hardware/software platform, that integrate a number of sensors and communicate wirelessly. One of Qameleon's products, the QarVision™ Elevator Performance Monitor, has nearly all of the features required for a probe vehicle. It includes a 30 mW WiFi radio for wireless communication. A QarVision™ unit was modified to add a high-gain antenna, a GPS receiver, a switch box to simulate lights and wipers, and sensors for acceleration, outside temperature and humidity, and ambient light. Its user interface was modified to display real-time probe vehicle data: acceleration and speed graphs, location, altitude, heading, speed, and sensor values. All data is also stored on-board. The QarVision™ graphing and data base program was modified to handle the probe vehicle data.

Initial testing along the I-19 WiFi Corridor showed that the 30 mW QarVision™ radio was insufficient to maintain a connection with the WiFi network. The radio was replaced with a PepLink Surf unit containing a 200 mW radio. This configuration maintained the connection for 65% of the distance, with intermittent gaps. The vehicle was monitored over the Internet by a user at a remote location. The user lost connection when the vehicle entered the coverage gaps. Analysis of acceleration data shows that the shape of the curve can be used to determine what the vehicle and driver are doing. The speed data from the GPS unit lags about 2 seconds behind actual speed, because the GPS is using location data to calculate speed once a second. Travel time was easily computed from the stored GPS time and location data.

Testing results show that WiFi can be used successfully to support probe vehicle systems. Continuous coverage is not necessary, since the vehicle unit can store data and transfer it when connected. The connection periods measured in the study are clearly sufficient to transfer the stored data. The advantage of using WiFi is that it is available now, and due to its popularity, WiFi equipment is inexpensive and readily available.

A follow-on study is recommended to:
- Transfer probe vehicle data automatically whenever the WiFi unit connects to the network;
- Determine processing distribution between the on-board computer and a centralized server;
- Identify and resolve issues when probe vehicles operate over multiple public WiFi networks;
- Determine the connection characteristics that are needed to transfer the data reliably, and determine the effects of weather, terrain, and other users on the connection characteristics;
- Test all of the above with a fleet of 10 probe vehicles.

I. Introduction

Each year, 43,000 people die on U.S. roads. Nearly half of those deaths occur because the vehicle left the roadway, or was involved in an intersection collision. The U.S. Department of Transportation is addressing this problem through its Vehicle Infrastructure Integration (VII) initiative.

The VII will enhance safety with an advanced, wireless data communication infrastructure, designed to collect and disseminate information to prevent accidents. Vehicles will communicate with other vehicles, and also with the infrastructure. As currently envisioned, government transportation agencies will install a system of roadside units that will communicate with properly equipped vehicles using Dedicated Short Range Communications (DSRC) at the 5.9 GHz radio spectrum. Vehicle manufacturers will be required to install DSRC communications equipment in all new vehicles.

The VII will also gather important information regarding roadway and traffic conditions. Vehicles contain a large number of sensors that can provide information useful for traffic management. For example, outside temperature, windshield wiper status, and traction control system activation can indicate hazardous weather conditions. Speed and location can be used to calculate travel times and pinpoint congestion. Data from a single vehicle is not sufficient for traffic management purposes; aggregated data from many vehicles is required. When vehicles are used to gather and report information in this manner, they are called probe vehicles. An important component of the VII initiative is the use of probe vehicle data for traffic management.

Building the VII infrastructure of roadside units will be expensive. It may be many years before a significant portion of the infrastructure is in place. In the meantime, many cities and other public and private entities are installing WiFi networks along roadways. These enable the same capabilities as the planned DSRC infrastructure: wireless communication between properly equipped vehicles, and between a vehicle and a traffic management center. The communication between vehicles is accomplished by virtue of the local area network that each WiFi network node establishes with WiFi devices in its area. The communication between vehicles and the traffic management center occurs over the Internet.

Since it will be many years before the DSRC infrastructure is installed, it may be beneficial to use existing WiFi networks to begin implementing a probe vehicle system today. If WiFi networks become ubiquitous, they could eliminate the need for a DSRC infrastructure. WiFi networks have the added benefit that they can support Voice over IP and Internet usage. Users of those services will help pay the cost of the networks, resulting in a more cost effective probe vehicle system.

WiFi has not previously been used as a communication mechanism for probe vehicles. Bishop [2005] performed a Quick Study for the Arizona Department of Transportation to analyze the potential of the I-19 WiFi Corridor to support a probe vehicle system. He concluded that a test study was necessary to determine the system characteristics.

Qameleon Technology designs and builds instruments, based on a common hardware/software platform, that integrate a number of sensors, and communicate wirelessly via either WiFi or cellular. One of Qameleon's products, the QarVision™ Elevator Performance Monitor, has nearly all of the features required for a probe vehicle.

The purpose of this Quick Study is threefold: 1) to modify the Qameleon platform to communicate as many vehicle parameters as possible; 2) to test the communication properties of the platform along the I-19 WiFi Corridor; and 3) to analyze the resulting data to determine if a WiFi network is viable as a communications infrastructure for probe vehicles.

II. Background

There is widespread interest in probe vehicles in Japan and Europe as well as the U.S. This section gives an overview of recent work and current use of probe vehicles in these countries.

Probe vehicles are a component of the Intelligent Transportation Systems (ITS) that are being developed within the U.S. Department of Transportation (USDOT). According to their ITS web site [see ITS Web]:

> "Intelligent transportation systems (ITS) encompass a broad range of wireless and wire line communications-based information and electronics technologies. When integrated into the transportation system's infrastructure, and in vehicles themselves, these technologies relieve congestion, improve safety and enhance American productivity."

One of the USDOT program's ITS components is the Vehicle Infrastructure Integration (VII) initiative [VII Web]. The goal of the VII is to develop and deploy vehicle-to-vehicle and vehicle-to-infrastructure communication systems that can prevent vehicles from leaving the roadway as well as enable them to move safely through intersections. In addition, real-time data gathered from sensors on the vehicle can be transmitted to collection centers where it is analyzed to determine road conditions. Data collected in this manner is called probe vehicle data.

Although it is still evolving, the current plan for VII uses radios with Dedicated Short Range Communications (DSRC) at 5.9 GHz for communications between vehicles, and between a vehicle and the infrastructure. Vehicle manufacturers will include an On Board Unit (OBU) on all new vehicles, containing a Global Positioning System (GPS), a DSRC transceiver, and a means of reporting data from existing on-board sensors. Government transportation agencies will install a system of Roadside Units (RSU), each containing a DSRC transceiver and a means of communicating with an aggregation point. The RSUs will not be spaced closely enough for continuous communication with vehicles, so vehicles will store the data they collect between RSUs to transmit as they pass an RSU. All data collected from vehicles would be anonymous to ensure privacy of drivers and vehicle owners.

Considerable research and development is being done on probe vehicles and data analysis in the public sector in the U.S., Europe, and Japan. Several studies have developed analytical methods to calculate speed, travel time, delays, or other traffic information from probe vehicle data, and then used simulations to test their approach. For example, Smith et al. [2006] developed a technique to divide roadways into zones, and to determine parameters, such as the number of vehicles tracked or the time between each position reading, based on the traffic conditions in each zone.

Numerous projects have developed techniques using input data from probe vehicles to predict travel time. The following examples are representative of the field. Yang [2005] developed a method using non-linear state space to predict travel times on arterial roads. Shalaby et al. [2006] described a software system that combines location/time data from probe vehicles with a geographic information system to determine travel times on specific road segments. Cell phones enabled with GPS can be used to track individuals as they travel and compute travel times, as described by Hato [2006]. Yamane et. al [2005] developed a method that permits relatively long travel intervals from probe vehicles to be used to predict accurate travel times.

Some state governments in the U.S. have been actively incorporating probe vehicle data into their existing traffic management systems. The University of Washington is working with the Washington State Department of Transportation (WSDOT) to develop procedures and guidelines for integrating probe vehicle data into large traffic management systems [Brodin 2006]. The

University of Washington and WSDOT have also developed “virtual sensors” to fill in gaps in speed data where there are no inductance loops. The virtual sensors are vehicles equipped for automatic vehicle location, which can be tracked over time to calculate speed. Coifman [2004] used probe vehicle data to examine the performance of a freeway management system in Columbus, Ohio.

While much of the interest in probe vehicles revolves around real-time data, they are also used to gather data for off-line reporting and analysis. Every year, the California Department of Transportation reports on the congestion levels of 2300 miles of its most heavily traveled freeways [CALTRANS Web]. Data for the report is gathered using both probe vehicles and loop detectors.

Several European countries have been actively pursuing probe vehicle technology (more commonly known as “floating car data”, or FCD, in Europe) for many years. Bishop [2005] presents an excellent summary of these projects. Several systems are available commercially. ITIS Holdings in the UK, and Trafficmaster in the UK, Germany, and Italy, follow the same business model. Customers who purchase the travel time information service must install a unit in their vehicle to receive the information, which also provides information back to the system, in effect making the customer’s vehicle both a supplier and consumer of FCD. A German firm, DDG, has installed FCD units in 40,000 BMWs and VWs, but has found the communication costs to be prohibitive. Both Mediamobile and Taxi-FCD use taxis as their floating cars. These are the most successful systems, since they rely on existing taxi communications to transmit data to a central location. Mediamobile and Taxi-FCD are in use and providing valuable traffic information in many cities in France and Germany.

Various European agencies have also performed large scale R&D projects involving FCD. The Road Traffic Advisor in the UK demonstrated the feasibility of floating cars communicating with roadside beacons operating at 5.8 GHz. The OPTIS program in Sweden demonstrated that FCD could produce better travel time data than fixed sensors. OPTIS used cellular to transmit the data, which is far too expensive for a full scale system. The European Space Agency used satellite communications in their Smart FCD project, demonstrating better coverage at competitive costs. Both BMW in their Extended Floating Car Data program and Daimler-Chrysler in their City FCD program used exception reporting to reduce communication costs.

With the formation of the European Union, these European countries have realized a need for standardization of the many information intensive processes related to vehicles. As a result, they have formed the Global System for Telematics (GST). This is an EU-funded integrated project to develop a standardized open architecture for telematics services [GST Web].

One of seven projects within the GST is Enhanced Floating Car Data (EFCD). The partners in this project include Fiat, Ford, Renault, Orange, and several smaller service providers. The EFCD project was completed in February 2007 with a successful demonstration. Realizing that many previous efforts to establish FCD systems were not sustainable because there was no viable business model, one design requirement of the EFCD is that FCD capabilities need to be bundled with another service, such as navigation, that consumers are likely to purchase.

The EFCD design includes detailed architectures for the in-vehicle component as well as the service center component [EFCD 2006]. The in-vehicle component includes access to all of the data on the vehicle data bus. It also requires inclusion of a vehicle location device such as GPS. The design does not mandate a specific communication technology, such as GPRS or GSM, since that will be determined at least in part by the other services that the EFCD is paired with. It does provide for vehicle to vehicle, vehicle to roadside, and roadside to service center communication.

In Japan, all FCD related programs are coordinated through the government agency known as ITS Japan [ITS Japan Web]. A major test project is currently taking place in Kanagawa

Prefecture, just south of Tokyo [Williams 2006]. From October 2006 through March 2009, nearly 10,000 Nissan vehicles with Nissan's CARWINGS navigation system will participate in the project as probe vehicles. Vehicles receive potential hazard information from a system of roadside optical beacons installed by the government. The vehicles send their route and other pertinent data to a central site by cell phone. The primary goals of the project are collision avoidance and improved navigation.

In 2005, Richard Bishop performed a Quick Study for the Arizona Department of Transportation to analyze the feasibility of the I-19 WiFi Corridor for probe vehicle data operations [Bishop 2005]. He reasoned that although WiFi has not been used in any previous probe vehicle projects, it offers the necessary capability of real-time data collection. Since the I-19 WiFi Corridor was designed to support mobile communications along the roadway, he believed it would be an ideal test bed for probe vehicle operations.

A wealth of data exists already or could easily be added within vehicles to enhance centralized traffic management. Bishop recommended that the following data would be useful if it could be transmitted from the probe vehicle: vehicle position, heading, and speed; ambient temperature; windshield wiper status; longitudinal acceleration/deceleration; lateral acceleration; anti-lock brake system activation; traction control system activation; suspension; and obstacle detection.

Bishop proposed several possible methods for extracting travel time of vehicles using the WiFi network. To minimize the cost of equipping probe vehicles, several of the proposed methods would analyze properties of the radio signal between the network's nodes and a common WiFi device already in the vehicle, such as in a laptop or PDA. Since many government agencies, public utilities, private companies, and even individuals, routinely carry such devices in their vehicles, the pool of probe vehicles would be large. The methods he proposed to determine travel time include recording and analyzing:

- the timing of connection and disconnection as the vehicle passes nodes;
- variation in signal strength of the on-board WiFi device relative to the nodes as the vehicle traverses the corridor;
- handoff times between the multiple antennas in the nodes.

Bishop also proposed adding GPS capability to on-board laptops. This would provide highly reliable travel time data, but would decrease the pool of potential probe vehicles due to the cost and effort required to add GPS. He also suggested connecting to the vehicle data bus to recover additional useful data such as windshield wiper status, air temperature, traction control activation, and antilock braking system activation. This implementation would probably require support from the automobile manufacturers.

Finally, Bishop recommended a follow-on project to test the many techniques he had proposed. An actual test of WiFi communications in support of probe vehicles is timely, as the number of planned and operational public WiFi networks in Arizona is growing rapidly. Public networks are available along I-19 between Green Valley and Rio Rico, in parts of Tucson, in Tempe, Avondale, and central Scottsdale. WiFi networks are being installed in Chandler, Gilbert, Superior, and along I-10 from Casa Grande to Tucson. Networks in Mesa and Phoenix are in the planning stages. As communities realize that public WiFi networks are a cost-effective means to provide broadband for their citizens, this list will grow.

III. The I-19 WiFi Corridor

The I-19 WiFi Corridor is a broadband WiFi wireless network that supports both data and Voice over IP (VoIP) along 40 kilometers of the I-19 freeway between Rio Rico and Green Valley, Arizona. I-19 extends from the border with Mexico at Nogales, Arizona north to Tucson. It is the southernmost portion of the CANAMEX corridor within Arizona, and will be the primary road system connecting the western US with Canada and Mexico. Much of the CANAMEX corridor passes through sparsely populated rural areas where broadband connectivity does not exist, and often, landline and cellular services do not exist either.

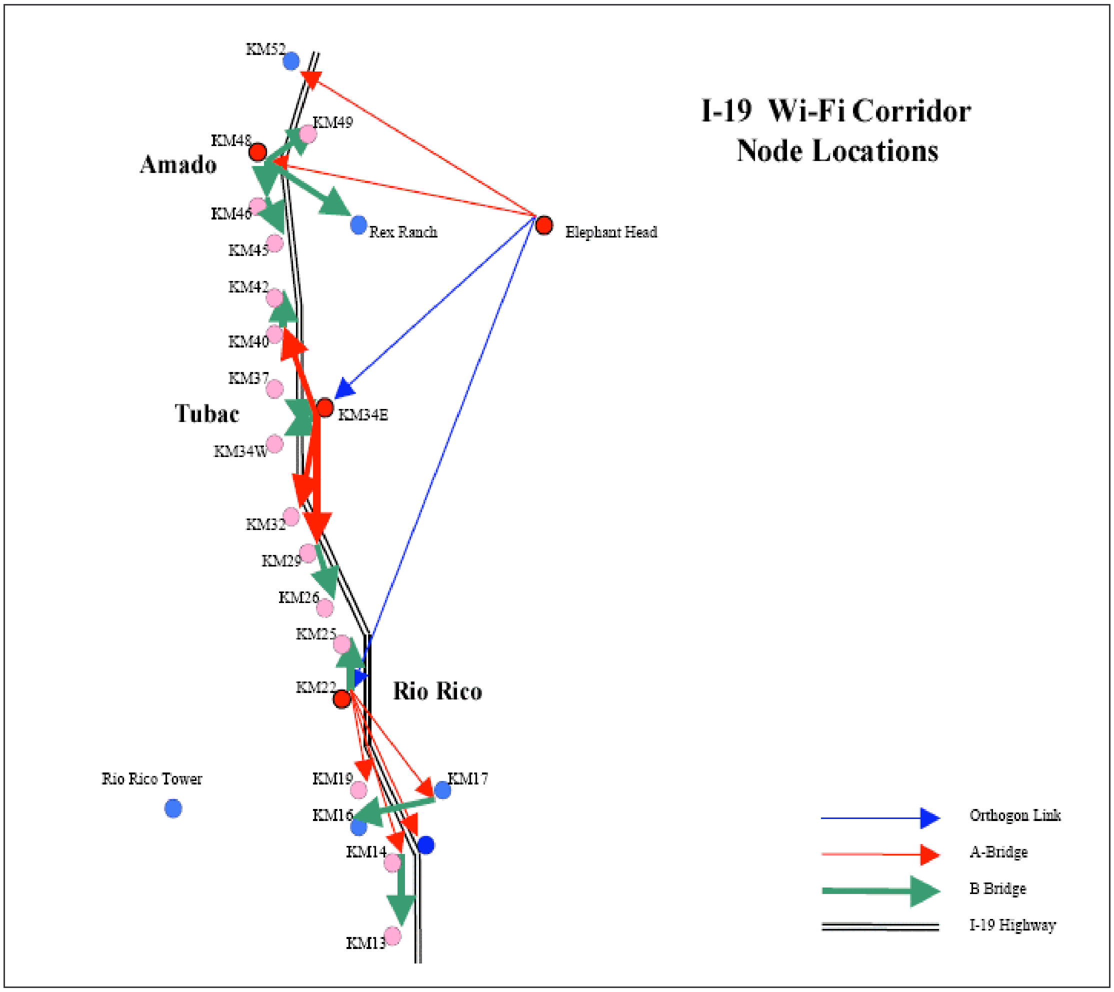


Figure 1. I-19 WiFi Corridor

In 2004, the Department of Homeland Security (DHS) awarded a grant to the Arizona Department of Emergency Management to build the proof-of-concept I-19 WiFi Corridor and demonstrate its utility for emergency and first responders. The Arizona Telecommunications and Infrastructure Council (ATIC) managed the project, and WI-VOD Corporation designed and installed the network. The project was completed in March 2006, and WI-VOD continues to operate the network. Figure 1 above[1] shows node locations along the Corridor.

[1] Diagram is taken from [ATIC 2006].

The Corridor was designed to provide continuous WiFi coverage along I-19. Low latency and fast, seamless handoff between nodes provide users with mobile broadband capability. While there are two known "dead spots" where connection is lost, tests during the DHS project showed that connection was reliably maintained for most of the route as vehicles traversed the corridor at speeds approaching 75 MPH. To maintain connectivity, vehicles must be equipped with a relatively powerful WiFi radio (at least 100 mW) and a relatively powerful antenna (at least 7 dB) mounted on the vehicle exterior.

To date, the I-19 WiFi Corridor has been evaluated and/or used by several government agencies as shown in Table 1 [ATIC 2006].

Table 1. WiFi Corridor Potential Client Agencies

Agency	Status	Use
U of A Telemedicine Program	Success	Transmission of voice, video, and vital statistics from health care facility in Amado to U of A Medical Center in Tucson.
Arizona Department of Public Safety	Evaluation	Enhanced connection speed for DPS officers. Auto theft interdiction.
Santa Cruz County Sheriff's Office	Success	Improved dispatching, communication, and information sharing.
Santa Cruz County HazMat	Success	Video transmission and control from 3 truck-mounted cameras.
Santa Cruz County Landfill	Success	Video transmission and control from 6 cameras.
Border Patrol	Evaluation	IP video surveillance. Secondary communication method.
Fire Districts	Evaluation	Earlier alerts and faster dissemination of graphical data.
Emergency Medical Transport	Evaluation	Comprehensive communication between EMT and hospital personnel during transport.

In addition to government agencies and schools, the I-19 WiFi Corridor network is available to the general public for an hourly, daily, or monthly fee.

Because the Corridor was designed to accommodate mobile applications, it is a useful test bed for probe vehicle monitoring. The WiFi related issues that are tested in this study include:

- coverage and connectivity along I-19,
- automatic authentication and login,
- seamless handoff and retention of IP address.

IV. Study Approach

Qameleon Technology builds wireless instruments for different industries. These are small, self-contained devices with very fast processors, a lot of memory, analog and digital inputs and outputs, and several communication interfaces. These devices have no user controls or control panels. Instead they interface with a user by communicating with remote devices, such as PDAs, laptops, and desktop computers. They can be operated locally, or over the Internet. Each unit has a built-in WiFi radio, as well as a wired Ethernet LAN interface. They also have an optional GPRS cellular interface.

A Qameleon QarVision™ Elevator Performance Monitor was modified for the probe vehicle system. This system has a built-in accelerometer, and several analog and digital channels. Since it is a system that is designed to track motion, it was an ideal platform for this system. The components of the probe vehicle system are shown below.

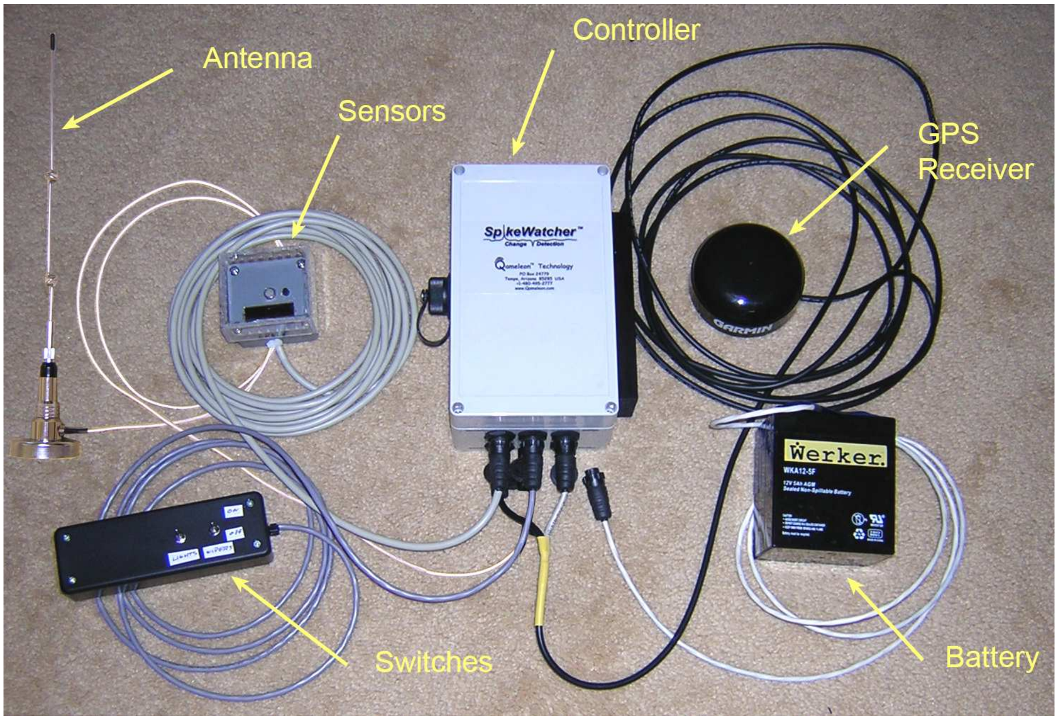


Figure 2. Qameleon Probe Vehicle Prototype System

The system consists of the following components:

Controller		A Qameleon QarVision™ module is used without modification. It contains a 3-axis accelerometer, but only the Y-axis (forward/reverse) is used for the demonstration. A QWIC-Cell™ cellular interface is included to allow for remote testing using a cellular network and the Internet.
Antenna		7dB magnetic mount omni-directional antenna.

Battery		A small 12v battery powers the unit in the vehicle.
GPS Receiver		A commercial GPS receiver is used to get the vehicle's location, altitude, heading, and speed. The precise time is also obtained from the GPS.
Switches		A simple set of switches is used to simulate the signals from the headlights and windshield wipers. In an actual installation, we would get the information from the vehicle's components.
Sensors		A simple module containing humidity, temperature, and ambient light sensors was constructed. This unit is mounted on the front of the vehicle to determine conditions near the ground. Other sensors may be more appropriate and can be interfaced later.

Switches **Sensors**

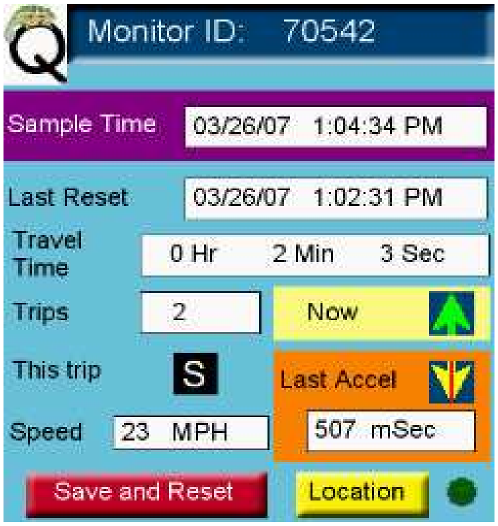
Figure 3. Component Details

Qameleon products are distributed computing systems. Every product has several applications that can be run remotely on demand. When the controller comes within range of a remote device (e.g. PDA or laptop), a list of these applications is transmitted to the remote. The user selects which application is to be run. The controller then sends a "configuration file" to the remote, which is used to tell the remote device how to run. The controller then loads its corresponding configuration file for the application. When both are loaded, the application runs, and the units communicate with each other.

The QarVision™ software was modified for the probe vehicle system. The basic system remained unchanged, but the applications that are available to the user were created specifically for this project. There are three applications that can be run on demand. These applications show you real-time data from the vehicle, as well as recording all of the vehicle data in a file for later analysis. The following screens were captured using a laptop via WiFi. The screens are exactly the same when using a PDA in the vehicle, or a desktop over the internet.

Vehicle Tracking

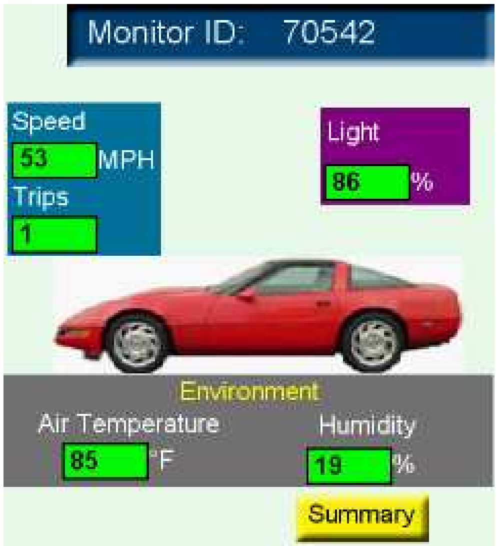
The Vehicle Tracking application provides a summary of the current status of the vehicle. The top screen shows information about the travel. The current travel time is derived from the time the system was reset until the current time. The **Now** and **Last Accel** boxes show that the vehicle is currently accelerating, and that the last "significant event" was a deceleration of .507 seconds. The **Trips** counter is the number of times the vehicle started and stopped during the current travel. The current direction of travel is south, at 23 MPH.



The middle screen shows the current information from the GPS receiver. The Latitude and Longitude are shown on the screen in Degrees-minutes-seconds, but they are recorded in 1/10ths of a second in the data file. The map shows the I-19 WiFi corridor. The icon shows the current position of the vehicle, and the direction of travel.

The bottom screen shows the current readings from the sensors located on the front of the vehicle. **Air temperature** and **humidity** are from sensors close to the ground. The **Light** field shows the relative ambient illumination. It may indicate poor visibility or night conditions. These readings are updated once per second.

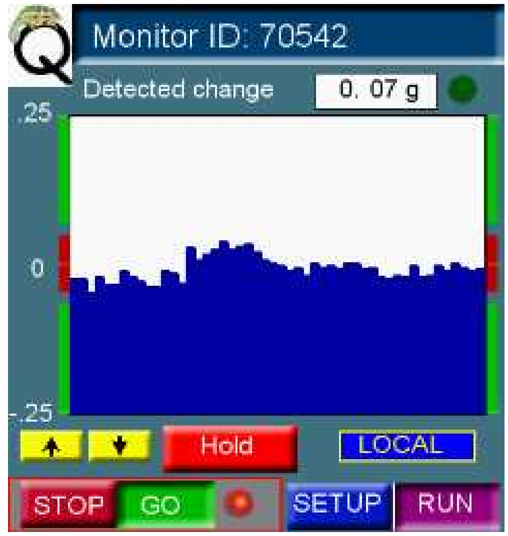
The status of the headlights and windshield wipers are indicated by highlighting the appropriate portions of the graphic. Currently, these are simulated using switches.



I-19 WiFi Corridor Probe Vehicle Tracking

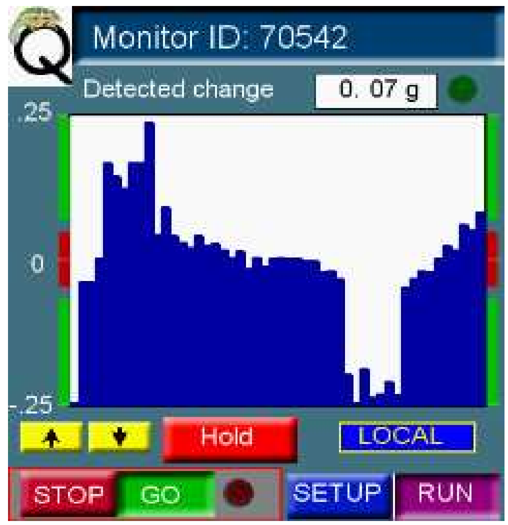
Acceleration

The Acceleration application tracks the acceleration and deceleration of the vehicle in real-time. The graph is updated 10 times per second, while the actual acceleration data is recorded in a file at speeds up to 100 times per second. The user can define what a "significant acceleration event" is. This is also used in the Vehicle Tracking application.



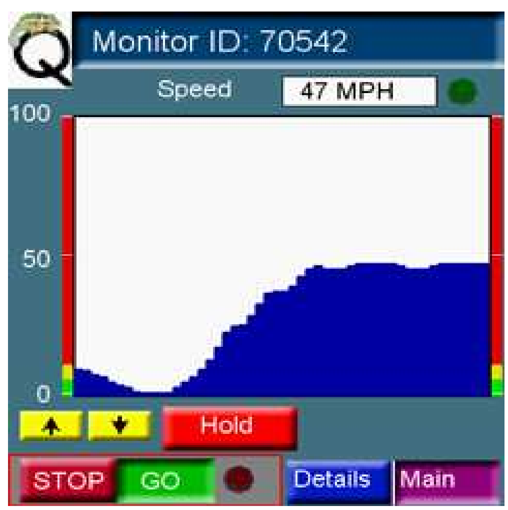
The screen on the top shows the accelerometer readings when the vehicle is traveling at a steady speed. Note that there is always some change in acceleration, usually due to the road surface, but may also be affected by the vehicle's suspension geometry.

The screen on the bottom shows the vehicle accelerating rapidly, and then decelerating rapidly. These are considered "significant" and may be indicators of traffic conditions. They may also be affected by the transmission shift points. The duration of the acceleration event is also used to determine its significance.



Vehicle Speed

The Vehicle Speed application tracks the speed in real-time, updating the graph every second. The speed is derived from the GPS signal, not from the vehicle's systems. The first screen shows the current speed of the vehicle.



Vehicle Speed

The second screen shows a summary of the speed since the application was started, including the maximum speed, the average speed, and the duration of the test.

The probe vehicle system displays current information on the remote device. In addition the system continually stores more information in the controller. No information is lost in the event that the communication is disrupted.

The probe vehicle system captures and records data in two ways. The controller is continually sampling the sensors at a high speed (1000 samples per second) to identify significant events. In the Acceleration application, the user can specify that the acceleration events be recorded continually or only when a “significant” event occurs. The Vehicle Tracking application records “significant” events when they occur, and background readings at a user-specified interval. The user has control over how and when the data are recoded. The data that are recorded are summarized in the following table. Every sample is stamped with date and time (nearest second or mSec, as appropriate) of occurrence.

Table 2. Data Classes and Characteristics

Acceleration			
	Acceleration	When significant event occurs, or Continuous for 1 Sec – 1000 Sec	Magnitude (.01g) at 1 Hz to 100 Hz
	Sensor 2 (not used)	Same as acceleration, or Periodically (1 Sec – 24 Hrs)	Depends on sensor
	Sensor 5 (not used)	When significant event occurs, Periodically (1 Sec – 24 Hrs)	Depends on sensor
	GPS latitude	At end of acceleration event	deg min .1sec
	GPS longitude	At end of acceleration event	deg min .1sec
	GPS altitude	At end of acceleration event	.1M
	GPS heading	At end of acceleration event	deg
	GPS speed	At end of acceleration event	.1 KPH

Table 2. (con't) Data Classes and Characteristics

Vehicle Tracking			
	Acceleration events	When significant event occurs	Magnitude (.01g) and duration (mSec)
	Temperature	Periodically (1 Sec – 24 Hrs)	0 - 250° F
	Humidity	Periodically (1 Sec – 24 Hrs)	0 – 100%
	Light level	Periodically (1 Sec – 24 Hrs)	0 – 100% full daylight
	GPS latitude	Periodically (1 Sec – 24 Hrs)	deg min .1sec
	GPS longitude	Periodically (1 Sec – 24 Hrs)	deg min .1sec
	GPS altitude	Periodically (1 Sec – 24 Hrs)	.1M
	GPS heading	Periodically (1 Sec – 24 Hrs)	deg
	GPS speed	Periodically (1 Sec – 24 Hrs)	.1 KPH
	Wipers	When a change occurs	ON/OFF
	Lights	When a change occurs	ON/OFF

Other measurements are possible. The data are recorded and transmitted in a compressed form to minimize communication volume. The stored data can be wirelessly retrieved from the controller on demand.
The information from the probe vehicle system is transferred to a PC where is it stored in a Microsoft Access database. The probe vehicle system has a graphical program for analyzing the stored data. This program is a modification of the EPM program used for the QarVision™ system. The user can display the data in different ways to examine the relationship between different aspects of the vehicle's travel. The sample graph, shown in Figure 4 below, plots the "significant acceleration events" over time, along with the vehicle's speed.

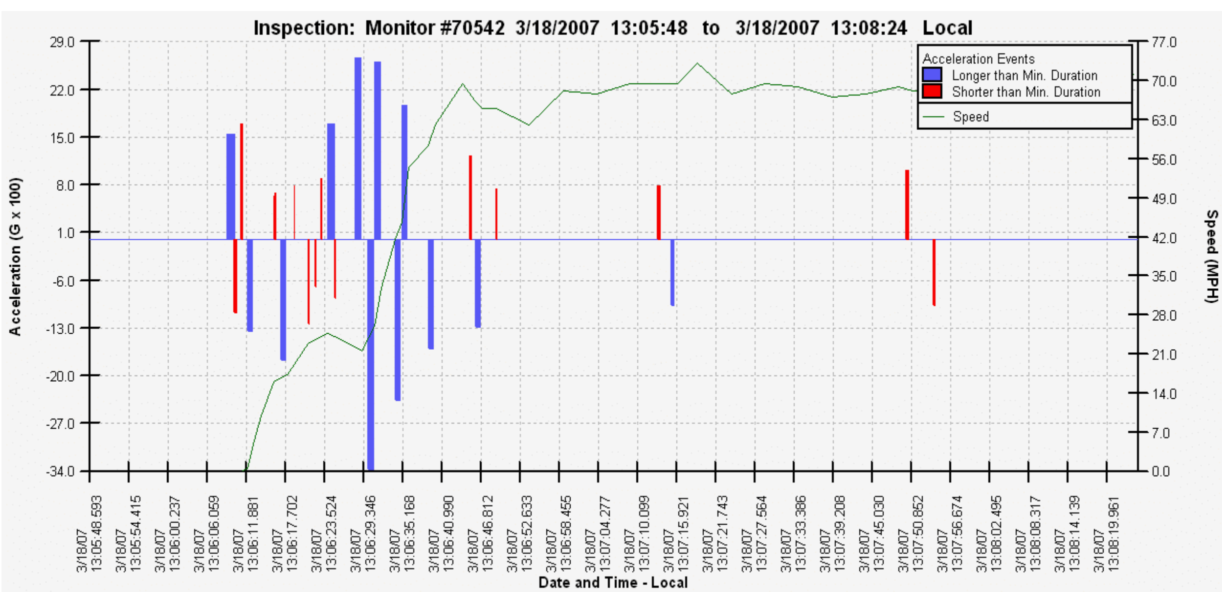


Figure 4. Sample Graph of Events vs Time

In this demonstration project, the probe vehicle hardware was installed in a passenger car. The system was temporarily installed, and can be easily moved to another vehicle. There are no electrical connections to the vehicle. All of the components can be installed in 15 minutes.

The vehicle monitor unit is placed on the passenger-side floor. It is powered by a small 12v battery. The unit is placed to minimize false accelerations due to the suspension geometry of the car. The wiper/lights switch box is on the seat.

The temperature, humidity, and light sensors are attached to the front of the car, in front of the radiator. The sensor unit is located approximately 12” above the road surface.

The GPS receiver is located inside of the vehicle under the rear window.

The WiFi antenna is magnetically mounted on top of the car to allow for omni-directional reception from the access points. A PDA is shown wirelessly receiving the signal from the unit.

Figure 5. Probe Vehicle Installation Details

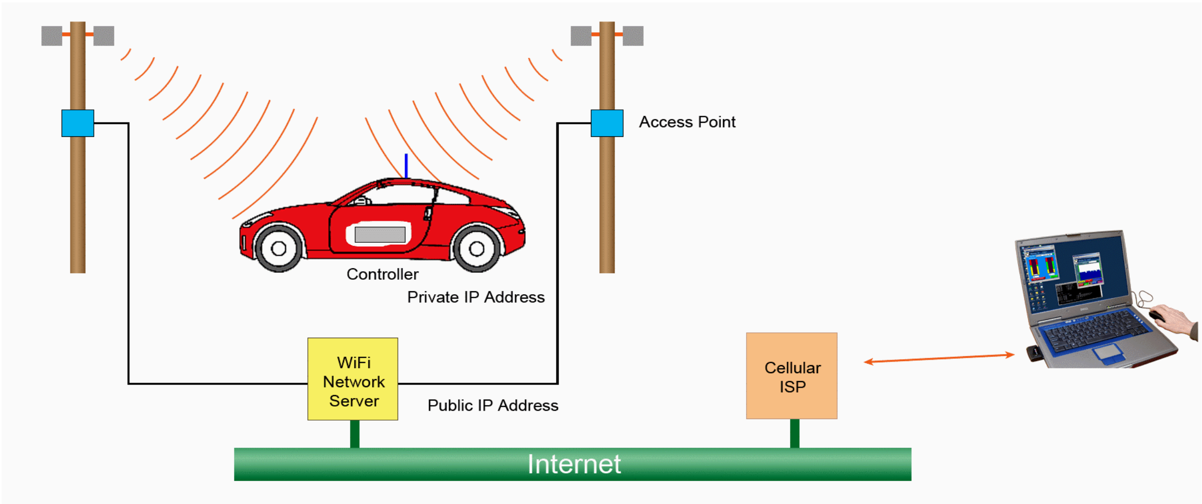


Figure 6. WiFi Communications Diagram

The system for this demonstration is shown in Figure 6, above. The I-19 WiFi corridor consists of several access points located on utility poles or buildings near the roadway. These access points have directional antennas that are aimed along the roadway in both directions. There are also omni-directional antennas that are used to communicate with clients in close proximity of the access points.

The coverage areas of the access points may or may not overlap with each other. The access points are connected to a server that is dedicated to this corridor. The server is connected to the Internet. A laptop was used with a cellular broadband interface to watch the vehicle in real-time, although any computer with access to the Internet will work.

In order to access the probe vehicle from the Internet, it was necessary to provide a public address for the QarVision™ controller. The vehicle itself is on a private wireless network with the access points and other WiFi devices. The WiFi Network Server has a table that maps the public IP address of the probe vehicle system to the private IP address of the vehicle. The vehicle's controller was given a fixed IP address for this demonstration, but it is also possible to use a dynamically assigned address.

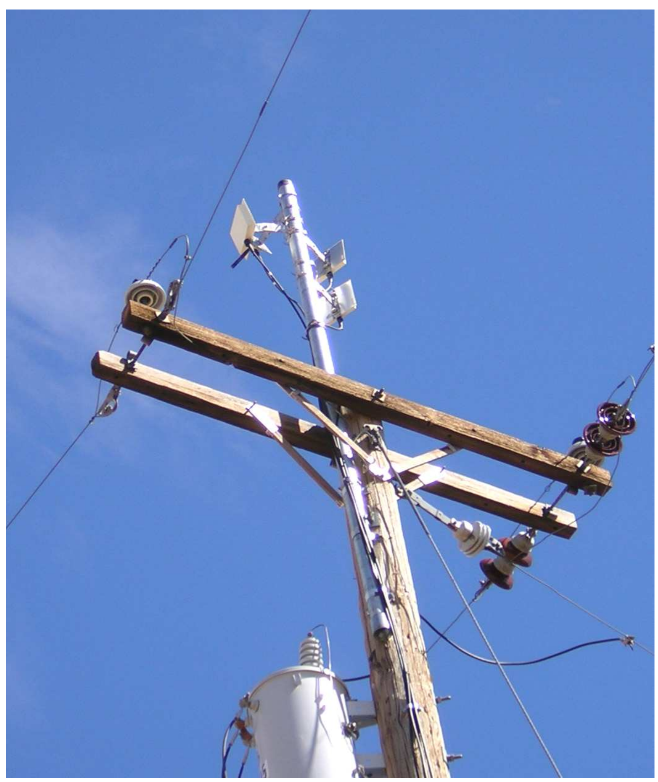


Figure 7. WiFi Antennas – Detail

Every device on the WiFi network needs to be authenticated. This can be easily done by using the unique hardware address (MAC address) of the controller's radio to identify it as a valid user. This is essential for devices that operate autonomously.

The cellular interface in the probe vehicle's controller was used for testing the system outside of the WiFi corridor.

Figure 8. WiFi Access Point – General Arrangement

V. Results

The initial test configuration used the 30 mW WiFi radio that is built into the QarVision™ unit, and the 7 dB antenna. During testing along the I-19 WiFi Corridor, this configuration maintained connectivity with a few of the WiFi nodes for 0.2 – 0.7 miles on either side of the nodes. At freeway speeds, the unit failed to connect with most of the nodes. This was deemed insufficient coverage for use with probe vehicles.

To improve the connection capability, a PepLink Surf 200BG-AP Access Point was added external to the QarVision™ unit. It was used, rather than the QarVision™ unit's internal radio, to connect to the WiFi network. The PepLink unit contains a 200 mW WiFi radio, and is interfaced to the QarVision™ unit's Ethernet LAN port with a cable. When combined with the 7 dB antenna, the connectivity improved dramatically.

The final test was performed on April 4, 2007. The test route ran from the Rio Rico Road interchange, north on I-19 to the Canoa Ranch rest area. The connection status light on the PepLink device was used to determine when the PepLink was connected to the WiFi network. The status (connected/not connected) was recorded in the data file using the windshield wiper switch: windshield wiper switched ON when connected, OFF when disconnected. The QarVision™ unit recorded all vehicle parameters every 5 seconds, except acceleration, which was recorded immediately whenever there was a significant acceleration event, and the wiper switch, which was recorded immediately whenever a change occurred.

The graph below shows the significant acceleration events along a portion of the test route. (This data was recorded during an earlier test run on March 26, 2007). An acceleration threshold of ±0.12g prevented insignificant accelerations from being recorded. Each acceleration event is shown as a bar, where the width of the bar is the duration of the event, and the positive or negative height of the bar is its maximum or minimum value over that duration. Red bars indicate that the event lasted less than 500 milliseconds, and blue bars indicate that it lasted longer. A graph of the speed is overlaid in green, with the speed scale shown on the right.

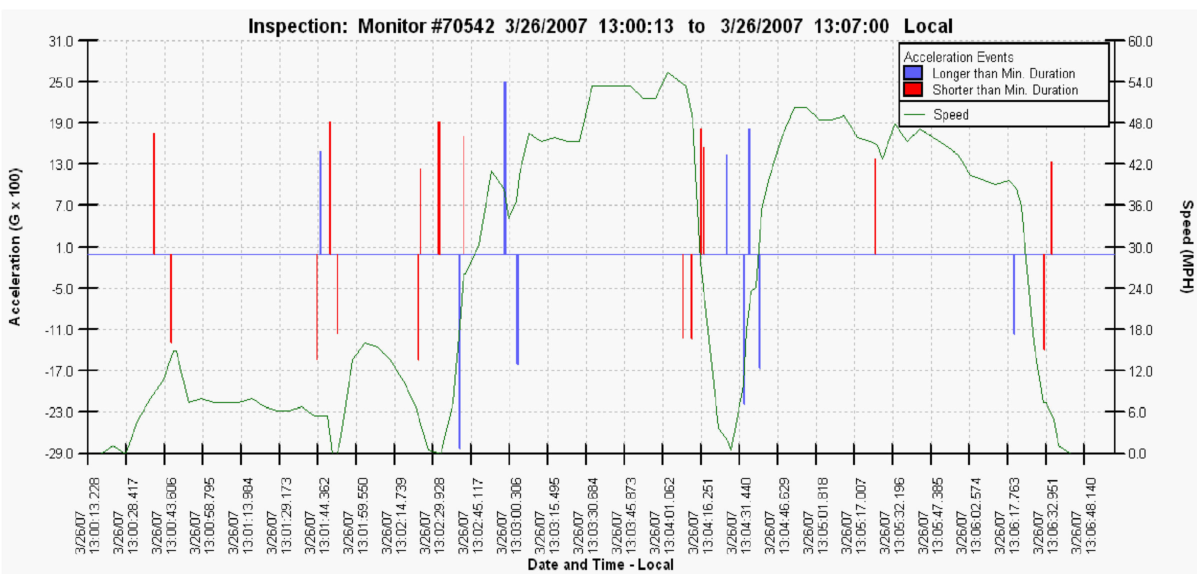


Figure 9. Significant Acceleration Events

When there is a significant acceleration or deceleration, there is a corresponding increase or decrease in speed. The speed change lags about 2 seconds behind the acceleration event. This is due to the fact that the acceleration sensor is sampled at approximate 1000 times per second, so accelerations are detected as they happen. Speed, however, is computed by the GPS, based upon change in location. Speed is reported by the GPS unit once per second. Speed as reported by the GPS always lags about 2 seconds behind the actual speed of the vehicle.

The graph below shows detail in the acceleration values during specific events. (These data were recorded during an earlier test run on March 26, 2007). Rather than plotting the acceleration event as a bar, the graph below shows actual acceleration values during the event.

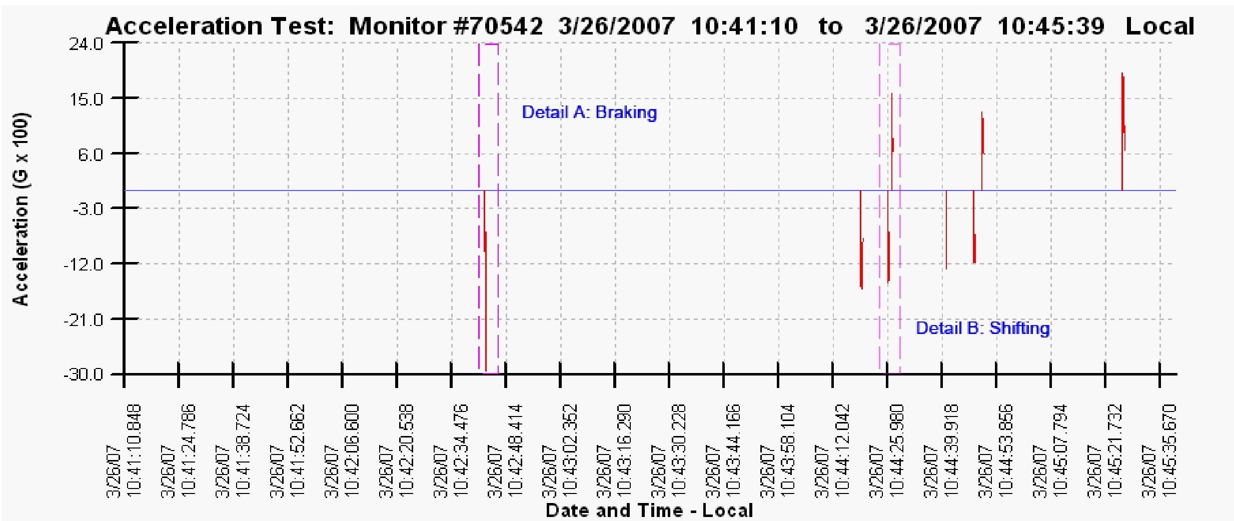


Figure 10. Mapping of Acceleration Values

A closer view of the areas outlined in purple (above) shows that there is a significant difference in the shape of the curves.

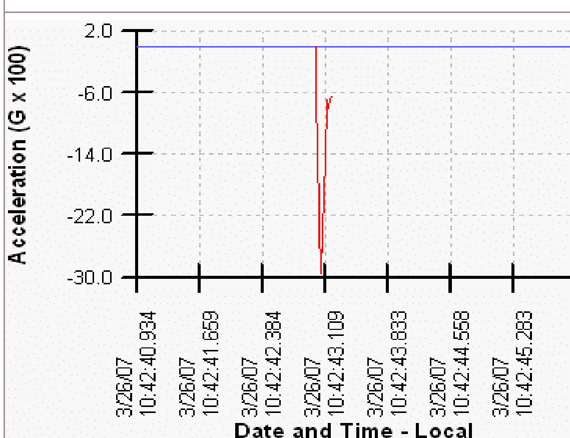
Detail A: Braking	
	Braking deceleration can be identified by the shape of the curve. The leading edge is abrupt, as is the trailing edge. In this example, the brakes were tapped hard, but for a short duration. Hard braking would have a longer duration, but similar leading and trailing edges.

Figure 11. Detail of Braking Dynamics

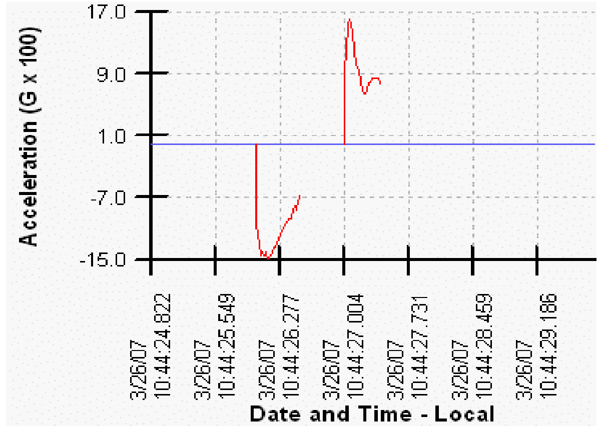
Detail B: Shifting	
Deceleration due to shifting has an abrupt leading edge, but a gradual trailing edge. The deceleration magnitude is usually less than that for braking. The deceleration event is usually followed by an acceleration event. Depending on the threshold settings, gentle accelerations may not be recorded.	

Figure 12. Detail of Shifting Dynamics

Figure 13 below shows the vehicle's speed plotted for the entire final test run. The hatched regions on the lower half of the graph show when the PepLink unit was connected with the WiFi network. The numbered areas of connectivity are shown on the map on the following page.

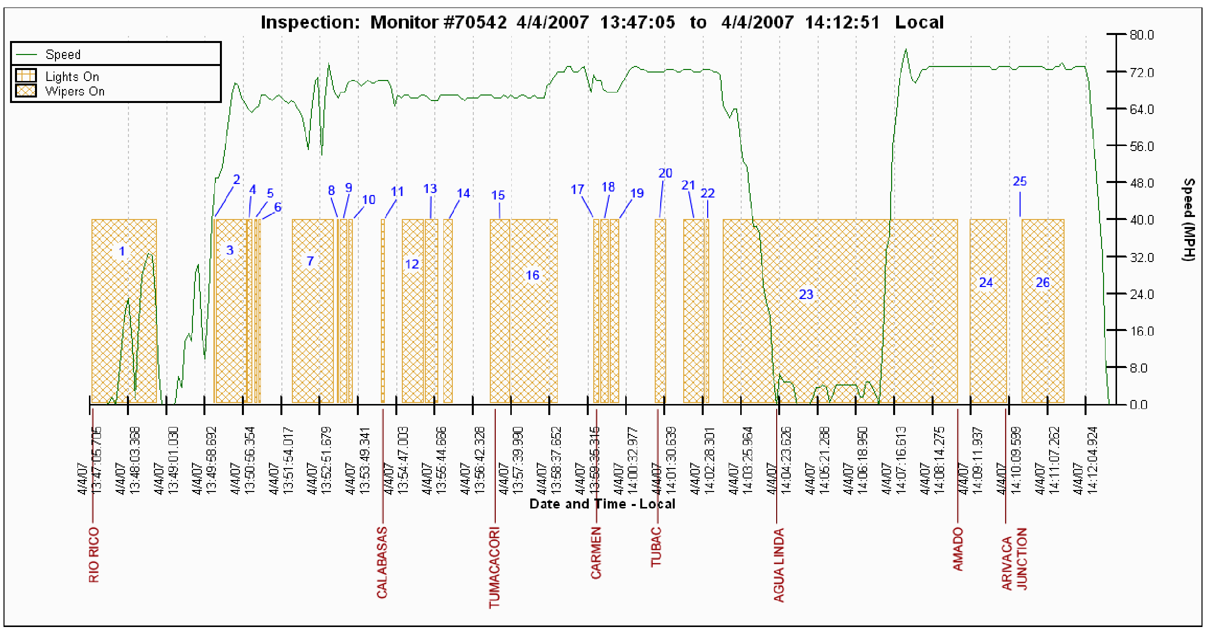


Figure 13. Speed Profile – Final Test Run

The travel times between the towns marked on the map are shown in Table 3. The time between Agua Linda and Amado appears to be excessively long. This is due to the Border Patrol check-point at the northbound Agua Linda exit. Travel times were only measured for the northbound trip.

Table 3. Observed Travel Times Between Towns on WiFi Corridor

Travel Times (Min:Sec)	Calabasas	Tumacacori	Carmen	Tubac	Agua Linda	Amado	Arivaca Junction
Rio Rico	7:19	10:08	12:41	14:13	17:10	21:45	22:58
Calabasas		2:49	5:22	6:54	9:51	14:26	15:39
Tumacacori			2:33	4:05	7:02	11:37	12:50
Carmen				1:32	4:29	9:04	10:17
Tubac					2:57	7:32	8:45
Agua Linda						4:35	5:48
Amado							1:13

Figure 14 on Page 22 shows the I-19 WiFi Corridor, which extends from the southern edge of Rio Rico to just south of the rest area at Canoa Ranch.

The red portions of the road show the gaps in connectivity. The WiFi nodes appear as green dots with yellow lines.

Segment	Time Traveled (Min:sec)	Distance Traveled (miles)
1	1:38	0.34
Gap	1:24	0.17
2	0:04	0.05
Gap	0:01	0.02
3	0:46	0.78
Gap	0:00	0.00
4	0:09	0.17
Gap	0:02	0.02
5	0:05	0.03
Gap	0:01	0.00
6	0:05	0.17
Gap	0:46	0.86
7	1:0	1.16
Gap	0:03	0.06
8	0:04	0.09
Gap	0:01	0.02
9	0:12	0.22
Gap	0:01	0.01
10	0:07	0.14
Gap	0:42	0.83
11	0:06	0.09
Gap	0:26	0.49
12	0:33	0.63
Gap	0:01	0.02
13	0:21	0.36
Gap	0:07	0.16
14	0:14	0.16
Gap	0:56	1.06
15	0:30	0.55
Gap	0:02	0.04
16	1:11	1.37
Gap	0:53	1.06
17	0:08	0.12
Gap	0:02	0.02
18	0:13	0.30
Gap	0:02	0.05
19	0:14	0.24
Gap	0:53	1.06
20	0:17	0.38
Gap	0:27	0.54
21	0:31	0.62
Gap	0:01	0.03
22	0:07	0.14
Gap	0:19	0.38
23	5:55	3.27
Gap	0:18	0.34
24	0:56	1.14
Gap	0:21	0.42
25	0:01	0.03
Gap	0:00	0.00
26	1:04	1.32

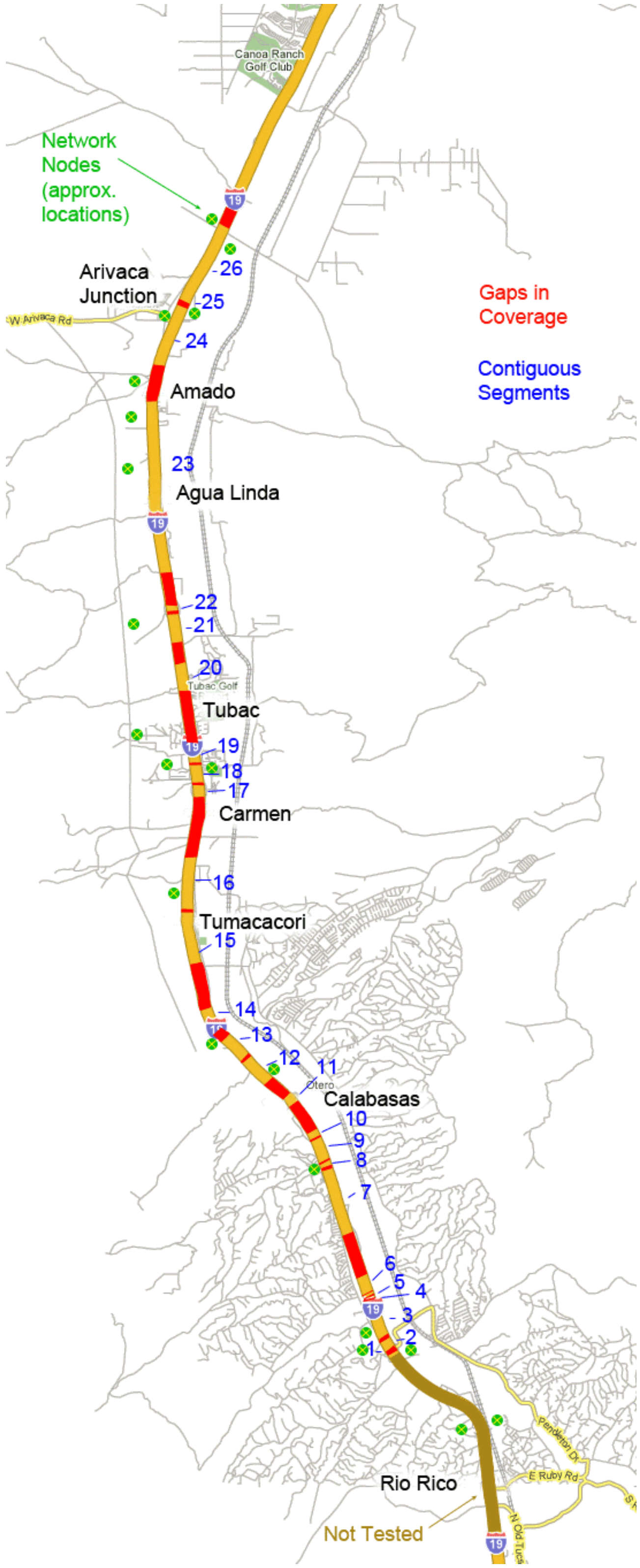


Figure 14. WiFi Corridor Connectivity – March 2007

Continuous WiFi coverage is not required to support probe vehicle operations. The future global VII system does not plan to have continuous coverage of vehicles from its roadside units. Rather, the vehicle and the roadside unit will exchange data as the vehicle passes. The vehicle will store its data until it can send it to the infrastructure. The exchange of data can be handled in the same way with WiFi.

During the final test, 50 bytes of vehicle data were recorded every 5 seconds. In addition, for every significant acceleration event, 24 bytes of data were recorded. The longest period during which there was no connection to the WiFi network was 84 seconds. This equates to 850 bytes of data recorded, plus the number of acceleration events times 24 bytes. Even with 10 events, this would total only 1090 bytes of data to be transmitted during the next connection period. The slowest WiFi transmission speed is 1 Mb (megabit) per second, or 125 KB (kilobytes). The periods of connection are clearly sufficient to transfer all of the vehicle data that is stored during unconnected periods.

Periodic sensor readings were recorded every 5 seconds (user selectable) from sensors located 12” above the road surface. No smoothing of the data was performed. The Light Level was recorded but not included in the graphing program. It varied from 71% to 91%, with an average reading of 85%.

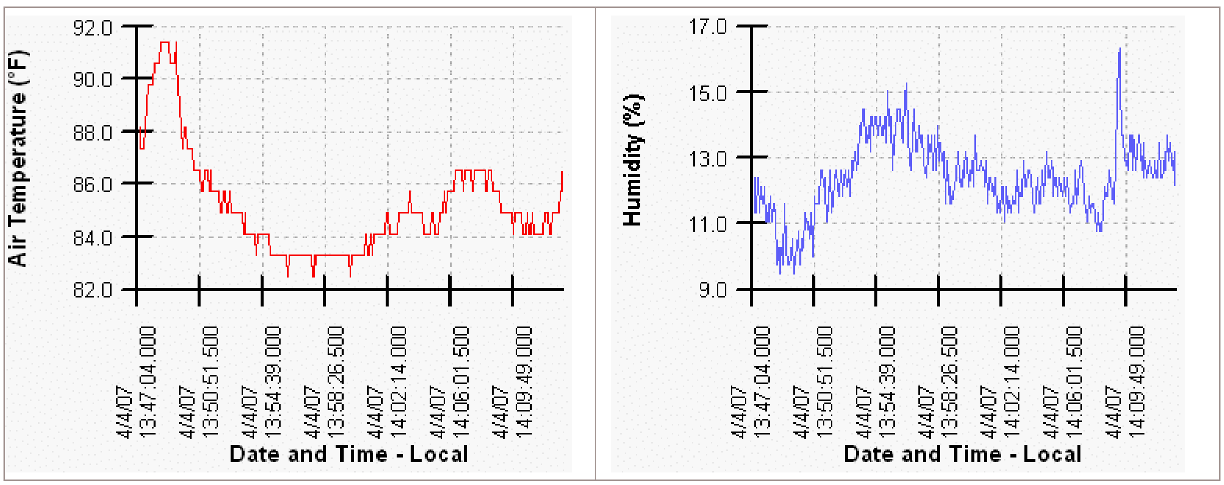


Figure 15. Weather-Sensor Data Monitoring Results

During the testing, the vehicle was monitored in real-time over the Internet from a fixed location (Tubac) using a laptop with a cellular broadband connection. The continuity was comparable to that shown in the data on the previous pages. The Qameleon software for real-time operation is designed to disconnect whenever the unit goes out of communication range. The user needs to manually reconnect to the device. This takes approximately 30 seconds, and was performed successfully whenever the continuity was maintained for a long enough time. Stored data is not affected by the communication.

There were no problems with overlapping nodes. Due to the speed of travel, the hand-off of the connections occurred with no noticeable problems. The authentication of the Qameleon controller and the IP address are maintained from node to node, eliminating the need to re-establish the session.

VI. Analysis of Findings

Several important lessons were learned as a result of this study:

- The WiFi network must automatically recognize, authenticate, and log in the vehicle's WiFi device. These connection tasks must occur quickly.
- The network must allow roaming from node to node. Handoff between nodes must occur quickly. Overlapping coverage must be handled gracefully.
- If a monitoring site needs to contact individual vehicles, those vehicles need a static IP address on the Internet.
- The vehicle's on-board device must have a powerful WiFi radio of at least 200 mW, and a high-gain antenna (at least 7 dB) on the exterior of the vehicle.
- The on-board device must recognize when it is connected to the network, and transfer and delete its stored data. The on-board device must remain connected to the network long enough to transfer the data.

The I-19 WiFi Corridor provides these necessary features. The MAC address of the WiFi device in the vehicle was used for authentication, and login was performed automatically by the network. The network was designed to allow roaming with a fast handoff from node to node. There were no detected problems with overlapping coverage. In this test system, the on-board device was assigned a static IP address so that an interactive session could be initiated from a remote location over the Internet.

A WiFi adapter such as those used for home wireless networks is not sufficient for the on-board device. Fortunately, many devices with more powerful radios are commercially available for under $200.

Public WiFi networks are not all the same. Their ability, or lack thereof, to handle automatic login, roaming, and static IP addresses, depends upon their software and hardware architecture. Additional testing is needed with other public WiFi networks, such as the one in Tempe, which were not explicitly designed with mobile applications in mind.

In this Quick Study, the on-board device stored all of the data during a test run, and never automatically transferred the stored data. The on-board unit transferred live data only, to a remote user for display on a PC. Further work is necessary to modify the on-board system to automatically transfer recorded data to the network when it is connected. Live, real-time data from individual vehicles may be useful, so retaining this capability should be considered.

A closely related issue is the length of the connection times in relation to the amount of data to be transferred. When the on-board WiFi radio connects to the network, the network must authenticate and login the device. This takes time. If the radio signal is weak, it may disconnect and reconnect frequently, and most of the connection time may be used for authentication. Also, if the connection is poor, packets may need to be retransmitted several times. Further study is needed to determine the essential connection characteristics for successful data transfer.

Other factors also impact the connection time and quality. Weather, terrain, other WiFi users, and even the vehicle itself will impact the connection. The on-board radio, processing, and storage capabilities need to be sufficient to meet the most demanding conditions. This can only be determined with further testing.

An important issue that needs further study is the amount of on-board processing that is necessary or useful before transferring the data from vehicle to network. There is a cost/benefit tradeoff since more on-board processing will reduce the amount of data that must be transmitted. This means that the vehicle needs to be connected to the network for less time, reducing the power requirements and cost of the WiFi radio. More on-board processing will require a faster and more capable computer, such as the one in the QarVision™ unit. Additional study of this issue would determine an appropriate level of on-board processing.

This Quick Study was performed on a single public WiFi network. As mentioned previously, WiFi networks vary in their capabilities. Just as they need the ability to roam from node to node within a single network, probe vehicles need to transition seamlessly from one network to another. Additional work is needed to determine how this can be done. At a minimum, each vehicle would need an account on every network. It may be possible to share static IP addresses if the number of vehicles logged on at one time is limited. A special type of account for probe vehicles, with limited access to the network, may be the best solution. A good test bed for these issues would be the Casa Grande and Tempe networks. They are geographically close, but have different architectures and were installed by different companies. This would provide an opportunity to investigate both the technical and administrative issues.

VII. Conclusions and Recommendations

This study has shown that WiFi is a promising communications technology for probe vehicles. Although it is difficult to achieve continuous connectivity between the vehicle and the WiFi network, this study shows that, under freeway driving conditions, the vehicle remained connected for approximately 65% of the distance traveled. To achieve this level of connectivity required a powerful radio and a high-gain antenna. Although these exceed what is ordinarily used in home networking, they are still commonly available and reasonably priced.

The U.S. Department of Transportation's Vehicle Infrastructure Integration initiative plans to construct a special purpose roadside network of wireless nodes for probe vehicles. It is likely to be many years before the VII infrastructure is built. Public WiFi networks are growing in popularity, and are available today. They are multi-purpose systems, which will keep costs reasonable. Numerous services in addition to Internet access and probe vehicles can be envisioned: vehicle maintenance, vehicle inspection, environmental monitoring, and mobile weather stations are but a few. Small-scale WiFi networks could be rapidly deployed in remote areas, and connected to a central server with a single cellular or satellite link. With a relatively small amount of research and development, WiFi networks could provide a viable probe vehicle addition to traffic management systems in the near future.

This study explored the viability of WiFi as a communication mechanism, but did not address the question of what data should be transmitted, or how that data can be used. This is a very important issue, in part because more data increases the system cost for hardware, sensors, and communications. Analysis of the needs, and implementation and testing with a real traffic management system would help to clarify the requirement.

*A follow-on project is recommended, to do the following:

- Transfer probe vehicle data automatically whenever the vehicle's WiFi unit connects to a network node;
- Determine the best distribution of processing between the vehicle's on-board computer and a centralized server;
- Identify and resolve issues when probe vehicles operate over multiple public WiFi networks;
- Determine the connection characteristics that are needed to transfer the data reliably, and also determine the effect of factors such as weather, terrain, and other users on the connection characteristics;
- Test all of the above with a fleet of 10 probe vehicles.

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